Constellation-X
Flight Mirror Assembly (FMA)

Mandrel Information Package

Prepared by the Constellation-X Project Team
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1. **Introduction**

This package provides background to assist interested organizations in developing ROM planning information related to producing forming mandrels for the Constellation-X Flight Mirror Assembly (FMA).

Interested organizations are invited to develop and submit the following ROM planning information related to providing a total of 326 forming mandrels as discussed below. The planning information desired should include, but is not necessarily limited to:

?   Overall ROM schedule - including mandrel blank acquisition, upfront preparations (facilities, training, etc.) time before delivery begins, subsequent delivery rates, and total schedule duration.

?   ROM cost estimate with sufficient detail to show mandrel blank acquisition costs, upfront and non-recurring costs, and production costs. A base cost for the system imaging requirement of 15 arc-seconds half-power-diameter (HPD) and a delta for the system imaging goal of 5 arc-seconds HPD are requested.

?   Summary description of facilities, metrology capabilities, personnel, that are not expected to be readily available and would have to be acquired to produce the Constellation-X mandrels.

?   For planning, assume three average delivery rates (once mandrel delivery begins) – 2 mandrels per week, 4 mandrels per week, and 6 mandrels per week.

A general description of the mandrels is given in Section 2.   Section 3 describes the Constellation-X Flight Mirror Assembly. Section 4 summarizes the Wolter I grazing incidence optics to be used.

2. Mandrel Description

A typical forming mandrel is shown in the figure below. The mandrels are referred to as "slab" mandrels. The figured and polished surface is the top surface and the curvature and height of each mandrel is different from all the other mandrels. The figured surface is a section of either a paraboloid or hyperboloid or revolution. The dimensions are shown in millimeters and are only representative of the largest mandrels. The mandrel width – the azimuthal or tangential direction - (573 mm) is determined by its corresponding radial position (see Section 3). The length (373 mm) – the axial direction – will be the same for all mandrels. The thickness (43 mm) is nominal. The radius of
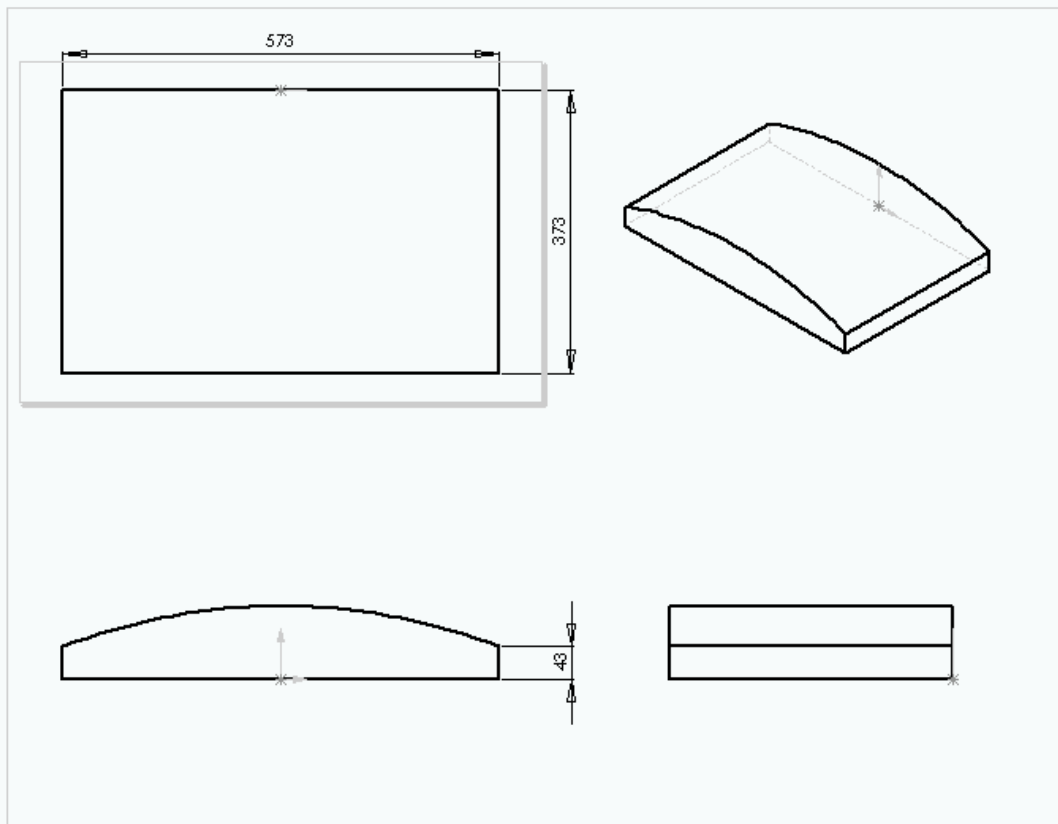

Figure 2-1 Schematic of Mandrel Blank.

curvature in the azimuthal direction ranges from approximately 650 mm to 150 mm. The axial figure is a Wolter 1 prescription summarized in Section 4. The back surface of the mandrel will not be flat, but may be hollowed out to achieve a more uniform wall thickness and better thermal properties. All corners and edges will be broken/beveled, and all surfaces (front, back, and sides) will be polished to control contamination. Some set of fiducials/registration marks will be required defining the center meridian or a line parallel to the optical axis. A fiducial will also be required indicating an axial reference point on the mandrel that is a known distance to the nominal focus.

The mandrel is used to produce mirror segments by positioning a glass sheet on the top surface of the mandrel. The mandrel and glass sheet are then heated to between 600 and 700 ºC. The glass softens and its lower surface assumes the surface of the mandrel. This is followed by an annealing process wherein the mandrel and segment are cooled. An important feature of the mandrel is that it must survive repeated heating and cooling cycles without loss of optical figure (the manufactured figure can accommodate CTE effects in the mandrel). Candidate mandrel materials are fused silica and Keatite (Schott) although Keatite remains to be demonstrated for the Constellation-X application. The vendor is not restricted to these two materials and alternative materials might be considered, e.g. SiC. The glass substrate material currently in use is D-263 which is selected for its smooth surface and comparatively low forming temperature.

The table below shows requirements for the extreme segments of the outer and inner mirror modules.

Shell	Paraboloid				Hyperboloid				
	Radius (large end, mm.)	Radius (small end, mm.)	Average cone angle (deg.)	Axial Sag (um,) P/V)	Radius (large end, mm.)	Radius (small end, mm.)	Average cone angle (deg.)	Axial Sag (um,) P/V)	Angular Width (deg)
Outer module, outermost	653.657	650.422	0.927	2.007	648.831	639.076	2.792	2.088	36
Outer module, innermost	326.830	325.211	0.464	1.005	324.415	319.536	1.398	1.044	36
Inner module, outermost	289.622	288.187	0.411	0.891	287.482	283.158	1.239	0.926	72
Inner module, innermost	159.82	150.097	0.214	0.464	149.730	147.478	0.645	0.482	72

Table of approximate mandrel radii, cone angles, and axial sags. Note these values are approximate and are given only to provide a guideline regarding mandrel size and shape.

Typical Tolerances consistent with the 15 arcsecond HPD system imaging requirement
Each mandrel is a precision figured and polished optic. The Wolter surfaces, parabolic and hyperbolic, taken together define an optical system having a focal length of 10,000 millimeters. Tolerances on the mandrel cone angles are approximately +/- 2.5 to 5.0 arc-seconds. Tolerance on the average radius is ±0.01 mm. Figure error tolerance is such that the RMS slope error, over the axial spatial frequency error bandwidth of 200 mm to 20 mm periods, is less than 2.5 micro-radians. The RMS amplitude over the axial spatial frequency bandwidth of 20 mm to 1 mm is less than 2.5 nm. The equivalent mandrel axial figure error power spectrum density (PSD), upon which this requirement is based, is shown in Figure 2-2. Mandrels consistent with mirror figure goals are also being considered. Their optical figure requirements are estimated to be between ~ 1/3 and 1/2 the RMS slope and amplitude of the figure requirements (between ~ 10 and 25 per cent of the figure error PSD).

The optical surface finish must be no rougher than 1.0 nm (10 Angstrom) for spatial frequencies higher than 1 mm^{-1} (1 inverse millimeter).

These tolerances are provided only to indicate the general degree of optical precision that is needed to meet the forming mandrel requirements and to provide a guide for developing the planning information that is desired. Section 4 presents additional information that is representative.

Error contributions must be reduced proportionately to meet the provisional budget consistent with the imaging goal of 5 arcseconds HPD.

An error budget for mandrel figure errors and geometry will be established and provided by the vendor (including radius, cone angle, etc.). Also, axial figure errors, from axial sag to roughness errors with periods ~ 1000/mm, and the full azimuthal figure error bandwidth, will be measured. The final metrology data will be part of a data package provided with each mandrel.
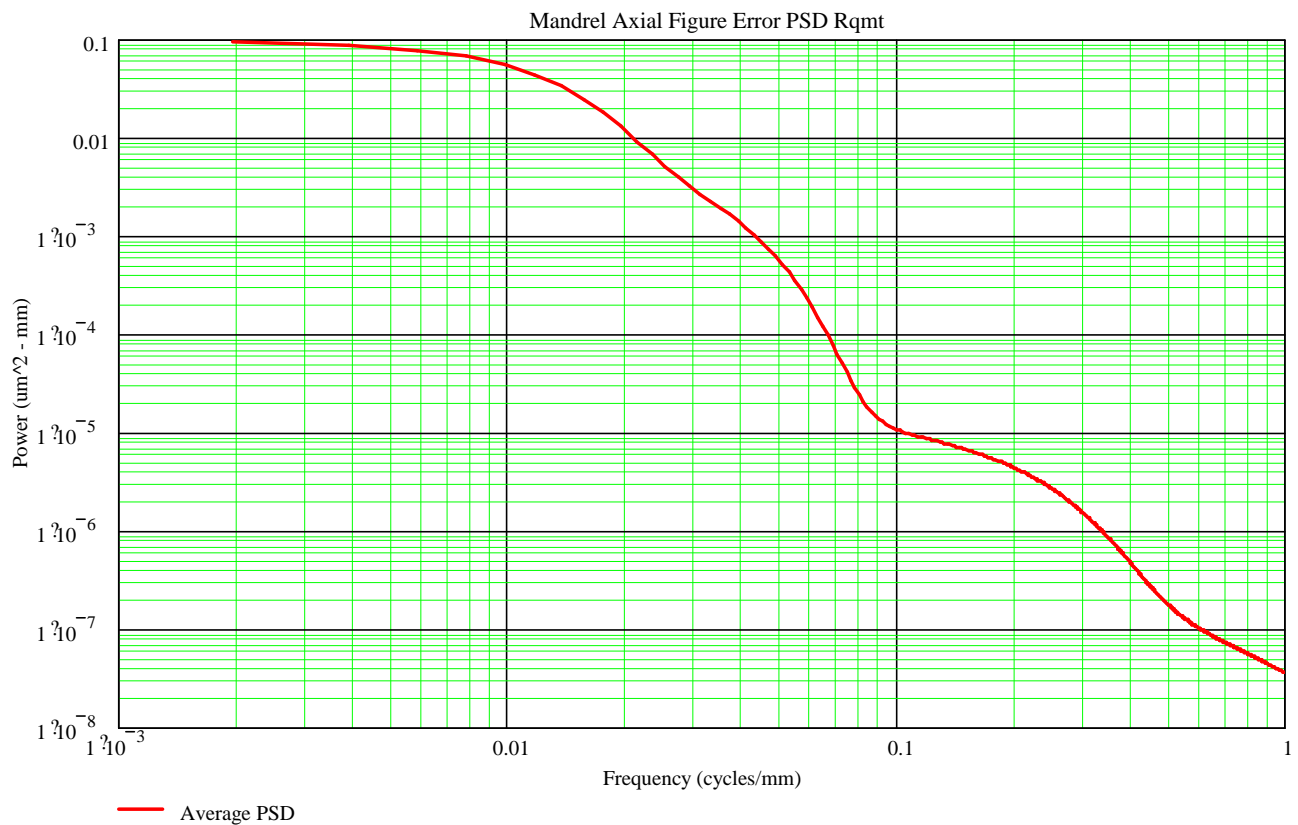

Figure 2-2 – Mandrel surface Power Density Spectrum (PSD).

3. Flight Mirror Assembly Description

Figure 3-1 shows a pictorial view of the mirror assembly organization. The assembly is divided into 5 inner angular sections or modules, 72 degrees wide each, and 10 outer modules, 36 degrees wide each. There are a total of 163 pairs of mandrels or a total of 326 individual mandrels required.
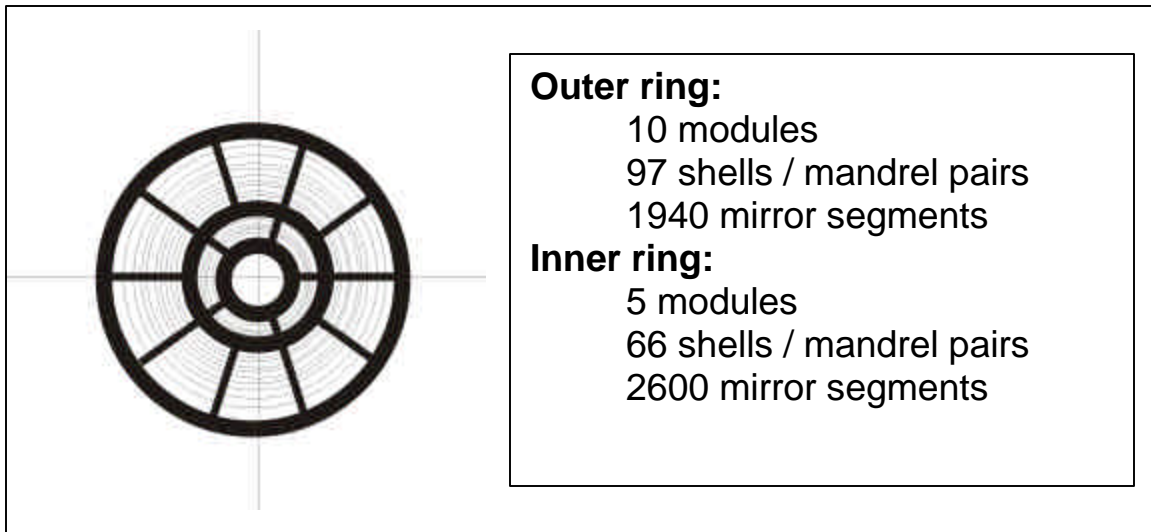
Outer ring:
  10 modules
  97 shells / mandrel pairs
  1940 mirror segments
Inner ring:
  5 modules
  66 shells / mandrel pairs
  2600 mirror segments

Figure 3-1 Flight Mirror Assembly Configuration

The approximate dimensions are:

Outer Section   O.D. =1300 mm   97 mandrel pairs spread over this annulus
                 I.D. = 720 mm

Inner Section   O.D.= 578 mm   66 mandrel pairs spread over this annulus
                 I.D.= 300 mm

4. Wolter 1 Optics

The Constellation-X Flight Mirror Assembly will use Wolter I grazing incidence optics. In the design, individual formed segments approximate a circular shell. Figure 4-1 defines the organization. The optical prescription is given by:

$$r_p{}^2 = (d + a + z)^2 - (a + z)^2 \quad \text{for the parabolic portion}$$

$$r_h{}^2 = (d + z)^2 e_h{}^2 - z^2 \quad \text{for the hyperbolic portion}$$

where d, e_h, and a are specified for each mandrel pair.

As an example just to show the precision level expected: for a pair whose intersection diameter is 1200 mm, the constants are:
d = 8.9898959067115
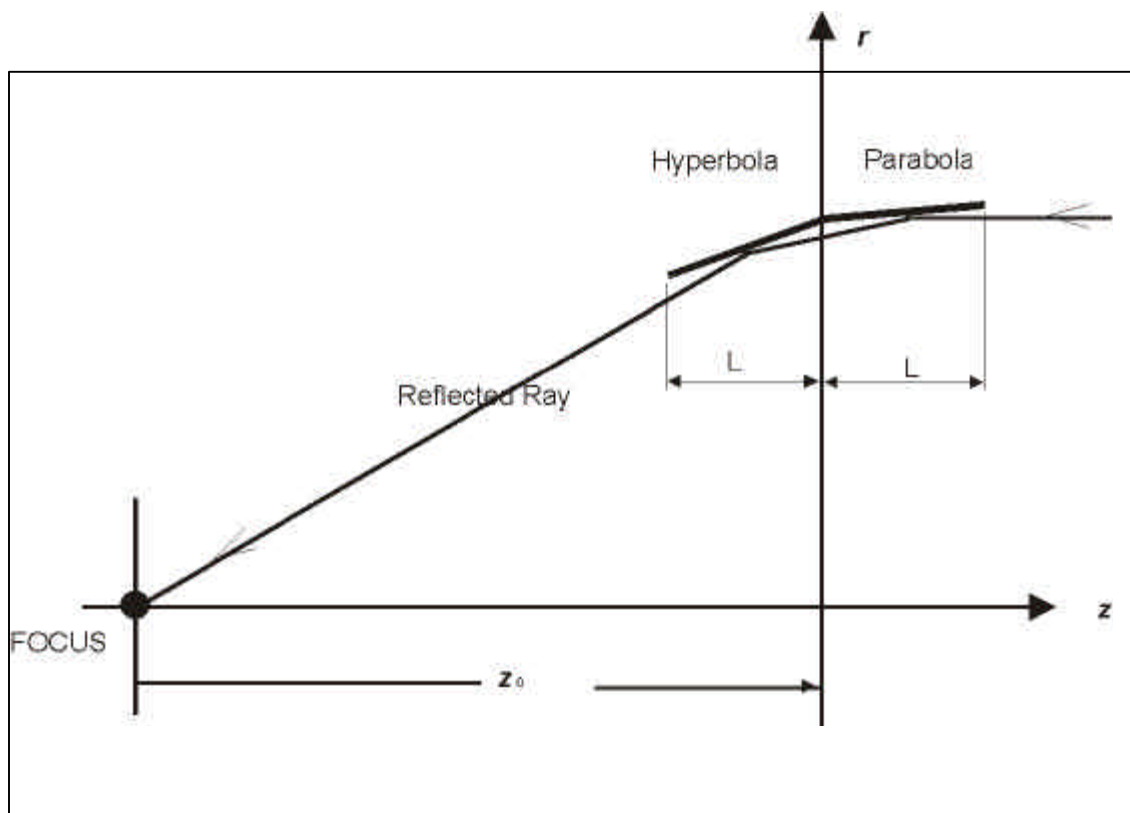e_h = 1.0008985854998
a = 10017.9838290945

Figure 4-1 Wolter I Grazing Incidence Optics – here z is only approximately the distance from intersection plane to best focus.

5. **Recent papers related to Constellation-X mirror development**

"The Constellation-X Spectroscopy X-ray Telescope: recent technology development," Robert Petre, John Lehan, Stephen O'Dell, Scott Owens, Paul B. Reid, et al., Proc. SPIE Int. Soc. Opt. Eng. **6266**, 62661Q (2006)

"Alignment and test of a Constellation-X SXT mirror segment pair," Scott M. Owens, Thomas Meagher, Theo Hadjimichael, John P. Lehan, David A. Content, et al., Proc. SPIE Int. Soc. Opt. Eng. **6266**, 62661W (2006)

"Fabricate and assemble: an alignment and integration method for next generation x-ray telescopes," William W. Zhang, Kai-Wing Chan, John P. Lehan, and Robert Petre, Proc. SPIE Int. Soc. Opt. Eng. **6266**, 62661M (2006)

"Development of lightweight x-ray mirrors for the Constellation-X mission," William W. Zhang, Kai-Wing Chan, David A. Content, John P. Lehan, Robert Petre, et al., Proc. SPIE Int. Soc. Opt. Eng. **6266**, 62661V (2006).

"Development of lightweight x-ray mirrors for the Constellation-X mission," William W. Zhang, David A. Content, John P. Lehan, Robert Petre, Timo T. Saha, et al., Proc. SPIE Int. Soc. Opt. Eng. **5900**, 59000V (2005)

"Development of lightweight x-ray mirrors for the Constellation-X mission," William W. Zhang, David A. Content, Stephen J. Henderson, John P. Lehan, Robert Petre, et al., Proc. SPIE Int. Soc. Opt. Eng. **5488**, 820 (2004)

"The Constellation-X Spectroscopy X-ray Telescope," Robert Petre, David A. Content, John P. Lehan, Stephen L. O'Dell, Scott M. Owens, et al., Proc. SPIE Int. Soc. Opt. Eng. **5488**, 505 (2004)

"Optical metrology for the segmented optics on the Constellation-X spectroscopy x-ray telescope," David A. Content, David Colella, Theo Hadjimichael, John P. Lehan, Joseph McMann, et al., Proc. SPIE Int. Soc. Opt. Eng. **5488**, 272 (2004)

"Equal-curvature x-ray telescope designs for Constellation-X mission," Timo T. Saha, David A. Content, and William W. Zhang, Proc. SPIE Int. Soc. Opt. Eng. **5168**, 346 (2004)

"Constellation-X spectroscopy x-ray telescope optical assembly, pathfinder image error budget and performance prediction," William A. Podgorski, Jay Bookbinder, David A. Content, William N. Davis, Mark D. Freeman, et al., Proc. SPIE Int. Soc. Opt. Eng. **5168**, 318 (2004)

"X-ray testing Constellation-X optics at MSFC's 100-m facility," Stephen L. O'Dell, Markus A. Baker, James M. Carter, David A. Content, William N. Davis, et al., Proc. SPIE Int. Soc. Opt. Eng. **5168**, 306 (2004)

"Constellation-X SXT optical alignment Pathfinder 2: design, implementation, and alignment," Scott M. Owens, Jason H. Hair, Jeffrey W. Stewart, Robert Petre, William W. Zhang, et al., Proc. SPIE Int. Soc. Opt. Eng. **5168**, 239 (2004)